Quantitative Measurements of Undulator Spatial Coherence at the ALS

It is no secret that undulator synchrotron radiation is partially coherent, but quantitative measurements on a beamline optimized for coherence experiments are less common. At the Advanced Light Source (ALS) at the Ernest Orlando Berkeley National Laboratory (Berkeley Lab), researchers from the Berkeley Lab's Center for X-ray Optics and the University of California, Berkeley, have applied a two-pinhole technique to measure the spatial coherence lengths in the horizontal and vertical directions of extreme ultraviolet (EUV) radiation at a wavelength of 13.4 nm. The high coherence measured with spatial filtering of the undulator radiation combined with the known scaling of coherent power with wavelength quantitatively demonstrates that high average coherent power is available at modern undulator beamlines.

The Berkeley group conducted its work on Beamline 12.0.1 at the ALS, an undulator beamline that was built by the Center for X-ray Optics (CXRO) as part of a large project funded primarily by the semiconductor industry to develop next-generation EUV lithography technology for printing ultrafine integrated-circuit patterns on silicon wafers. The ALS portion of the project consisted of acquiring the metrology capability necessary to verify the optical quality of reduction cameras and their associated optical elements [Synchrotron Radiation News, 10 (4), 10-12 (1997)].

At Beamline 12.0.1, this activity resulted in an award-winning, phase-shifting point-diffraction interferometer that, tests showed, could measure the optical quality of EUV cameras with an rms accuracy of at least $\lambda/330$ (about a third of an angstrom at the nominal 13.4-nm wavelength at which the cameras were designed to operate). Subsequently, CXRO built a new branch on the beamline that was dedicated to metrology for EUV lithography cameras, work that is contributing to the ongoing progress in the EUV lithography program whose sponsors now include European as well as American semiconductor companies. With this success in hand, which plainly depended on the spatial coherence of the undulator radiation, CXRO shifted the original interferometer primarily to basic research, including the quantitative characterization of the coherence properties of undulator radiation.

Beamline 12.0.1 begins with an 8.0-cmperiod undulator through which passes an ellip-

 $(d = 2\sigma)$ of 32 μ m in the vertical direction and 520 µm in the horizontal, and an emission half-angle θ of 80 µrad for the central radiation cone at the ALS operating electronbeam energy of 1.9 GeV. With the criterion for spatial coherence being $d \cdot \theta = \lambda/2\pi$, these beam specifications suggest one should expect for a wavelength of 13.4 nm to see a high degree of spatial coherence throughout the beam in the vertical direction but only over a fraction of the beam in the horizontal direction.

optics, after a horizontally deflecting mirror, an acceptance aperture (48 µrad) that is somewhat smaller than the central cone of the undulator radiation selects the most coherent portion of the beam. The beamline includes a variable-line-spacing monochromator with a spectral resolving power ($\lambda/\Delta\lambda$) up to 1100, but for most of the measure-

ments reported here the slits were opened to allow the natural undulator bandwidth ($\lambda/\Delta\lambda$ = 55) to pass. A spherical focusing mirror before the monochromator and a Kirkpatrick-Baez condenser system after the monochromator together reduce the beam size by a factor of 60 in both directions at the focus of the KB system where a mask containing multiple pairs of pinholes resides. A CCD detector images the radiation pattern passing through the pinholes.

For their measurements, the Berkeley group adopted a short-wavelength version of the Thompson and Wolf two-pinhole experiment in which the overlap of the pinhole diffraction patterns produces an interference pattern within the Airy envelope. The fringe visibility (difference between maximum and minimum fringe intensity divided by the sum) is tically shaped electron beam with dimensions recorded as a function of the separation

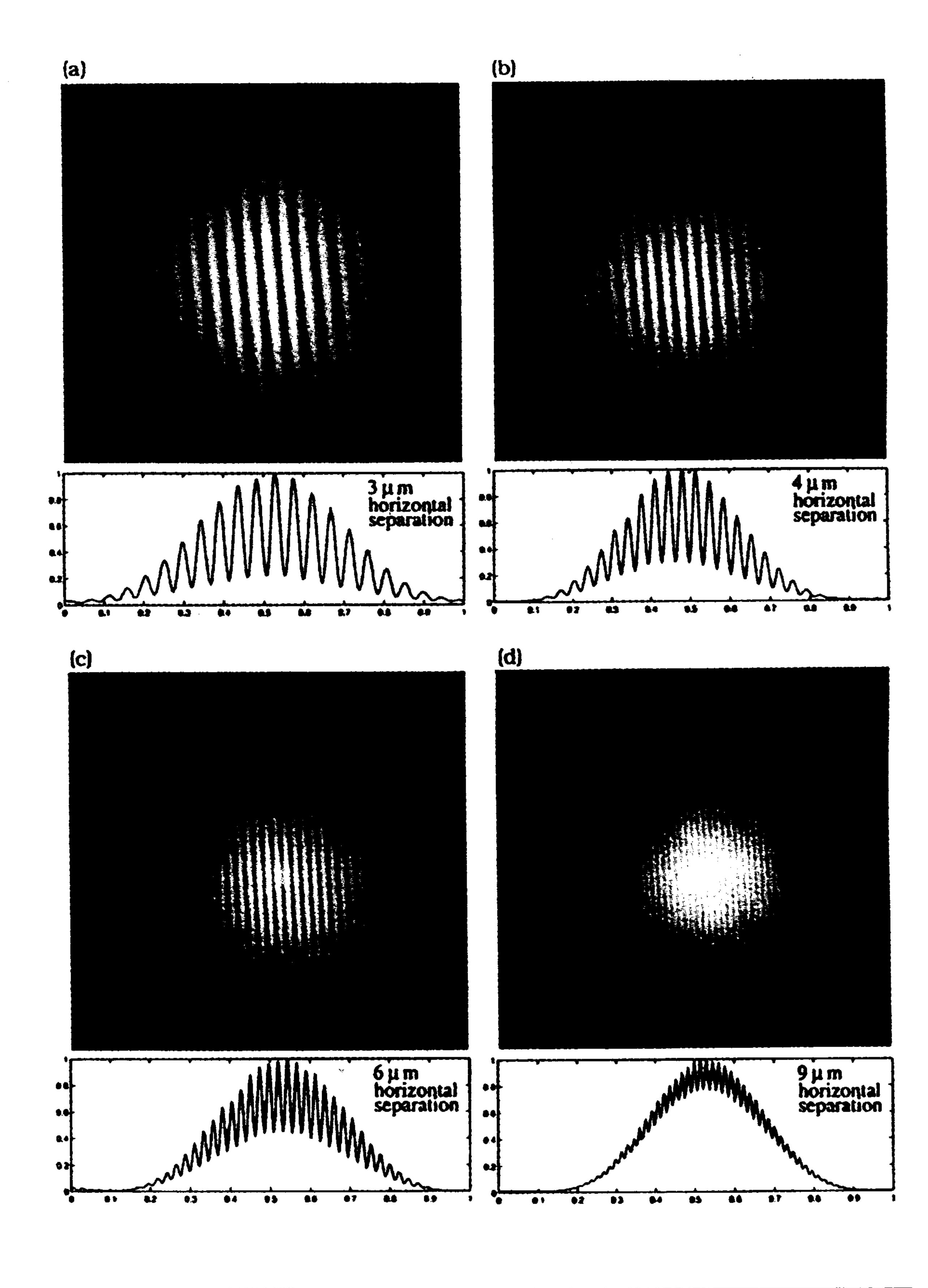


Figure 1: Interference patterns measured at Beamline 12.0.1 of the ALS for a series of nominally 450-nm-diameter pinhole pairs separated by distances from 3 to 9 µm. Actual pinhole diameters were in the range between 400 and 500 µm but were the same for any given pair.

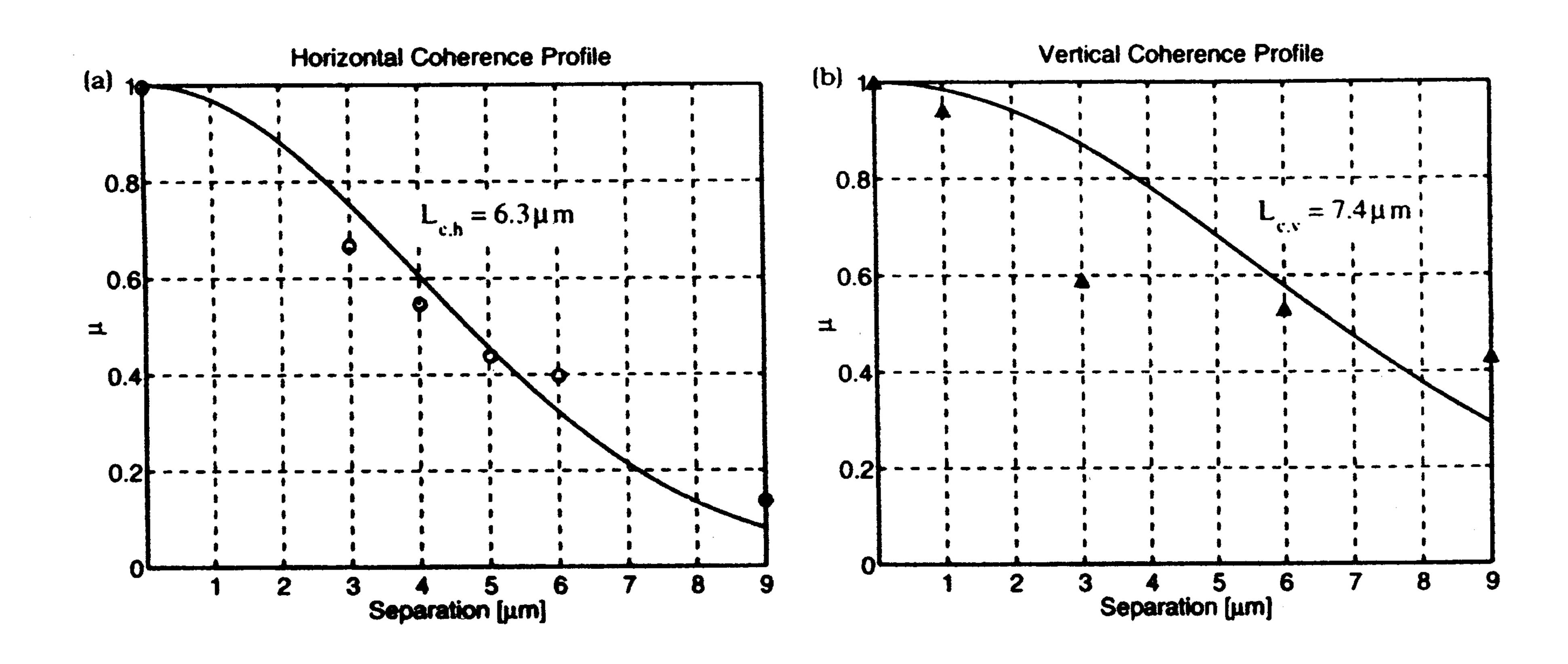


Figure 2. Measured values of the coherence factor μ as a function of pinhole separation in (a) the horizontal and (b) vertical directions. The coherence factor in these experiments is the same as the visibility obtained by Fourier analysis of an interference pattern.

between two identical pinholes. The interference modulations of the Airy envelope as the pinhole separation changes provide a direct measurement of the spatial coherence of radiation source, in this case the Beamline 12.0.1 undulator. For the technique to be accurate, the pinholes must satisfy three conditions: (1) they must be small enough that the fields within the pinholes are effectively constant;(2) the intensities at the two pinholes must be identical; and (3) the bandwidth of the source must be large enough to avoid temporal coherence effects in the interference fringes.

To meet these conditions, the researchers manufactured by electron-beam lithography pairs of nominally 450-nm-diameter pinholes (diameters ranged from 400 to 500 µm but were the same for each pair) in a nickel layer on a silicon nitride substrate with pair spacings from 1 to 9 μm . The 450-nm diameter is smaller than the expected coherence width, thereby satisfying the first condition. To achieve identical intensities, they made large numbers of measurements (50 or more), each with the mask displaced slightly differently relative to the incident beam. They then selected the measurement with the largest fringe visibility to represent the case with the most equal pinhole illumination. Finally, the natural undulator bandwidth, corresponding to a temporal (longitudinal) coherence length ($\lambda^2/2\Delta\lambda$) of 0.37 μm , satisfied the quasi-monochromatic condition.

Figure 1 shows measured two-pinhole interference patterns for four pinhole separations in the horizontal direction. Measurements for vertical pinhole separations showed generally similar patterns, but the fringe visibilities were somewhat larger. The researchers calculated visibilities by applying a two-dimensional Fourier transform to the standard formula for the interference pattern with measured values of the intensities. The results are shown in Figure 2, which plots the coherence factor µ (equal to the visibility for these experiments) as function of pinhole separation in the horizontal and vertical directions. As expected for radiation with a finite transverse coherence, the measured coherence decreases with pinhole separation. From these curves, they calculated transverse coherence distances of $6.3 \mu m$ and $7.4 \mu m$ in the horizontal and vertical directions, respectively.

Why is the coherence greater in the vertical direction when the acceptance aperture is circular? The answer lies in the asymmetric source size. In these experiments, the small vertical source size results in a vertical coherence width at the aperture larger than the aperture, which increases the vertical coherence. Comparison of actual measured and aberration-free simulated distributions of intensity and coherence showed the vertical coherence to be larger than the FWHM vertical beam size, indicating nearly complete coherence in the vertical direction, whereas the horizontal coherence is both

less than the vertical coherence and significantly less than the beam size. Aberrations in the beamline optics tend to increase the beam size and the coherence isometrics (beam profile for a fixed value of the coherence, such as $\mu = 0.5$).

Since some types of experiments require a more monochromatic beam than used in these measurements, the researchers also measured the effect on the coherence of the monochromator exit-slit width. For these measurements at a fixed value of the pinhole separation, they increased the acceptance aperture to pass the entire undulator central cone and varied the width of the exit slits, which open and close vertically. As they expected, the exit slits acted as a spatial filter, having a significant effect on spatial coherence in the vertical direction and only a small effect in the horizontal. For example, in the vertical direction, they found values of μ ranging from 0.94 at a slit width of 50 μ m to 0.38 at $400 \mu m$.

Finally, to measure the departure from sphericity of the two nearly identical spherical pinhole-diffracted waves, the group used standard Fourier-transform wavefront-reconstruction techniques to analyze the interference pattern recorded by the CCD detector for pinholes separated by 9 µm. Comparing the resulting wavefront with that calculated for ideal spherical waves resulted in a graph of the departure from sphericity (expressed as the rms value of the number of waves) as a function of the numerical aperture. For example, for the 0.025 numerical aperture typical of EUV optical testing, they obtained a value of $\lambda/330$, in agreement with earlier results by the EUV lithography metrology group.

In sum, these measurements of the spatial coherence properties demonstrate that high average coherent power is available at modern undulator beamlines.

CHANG CHANG
Center for X-ray Optics
Berkeley Lab

ART ROBINSON

Advanced Light Source

Berkeley Lab